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Review article

# Environmental sustainability in gynecologic oncology

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ABSTRACT

Climate change is a complex, global issue that is impacting human health in various ways, with healthcare being a significant contributor to carbon emissions in the United States. This review discusses the environmental impact of important aspects of gynecologic oncology care, including surgery, anesthesia care, radiology, chemotherapy, and radiation oncology. Operating room energy and material use is highlighted, with a focus on the environmental impact of robotic surgery. The contribution of certain anesthetic gases in increasing greenhouse gas emissions is addressed. Additionally, the environmental impacts of radiologic imaging, chemotherapy, and radiation oncology are also discussed. Despite the complexity of climate change, there are multiple strategies on the individual and institutional level that can help mitigate the environmental impact of gynecologic oncology care. Individual efforts include practicing red bag stewardship, limiting single use-supplies, decreasing the use of potentially deleterious anesthetics, and supporting research into alternative dosing for chemotherapy and radiation which requires less patient travel. Institutional strategies include investing in efficient HVAC systems, utilizing reusable and reprocessed materials and devices, and purchasing renewable energy sources. Both individuals and institutions can advocate with industry and government at all levels for practices and policies that support lower carbon emissions. By recognizing our role in reducing carbon emissions, we can work towards improving the well-being of our patients and the larger community.

## 1. Introduction

Climate change, a pressing, complex global challenge, has far-reaching implications for the planet and human health. A warming climate impacts health in a myriad of ways, such as an increase in heat related deaths, respiratory and cardiovascular impacts from poor air quality, and disruptions to the food supply from natural disasters (Andy and Kristie, 2019). From an oncologic perspective, increasing exposure to carcinogens related to climate change directly alters the normal pathways of cellular proliferation and differentiation leading to increasing rates of cancer (Bernicker et al., 2024). Indirectly, patients struggle to access appropriate medical care, including life-saving and palliative therapies, as the frequency of natural disasters increases (Bernicker et al., 2024).

The United States (US) is the second largest contributor to global greenhouse gas emissions, following closely behind China (United Nations Environment Programme. Emissions Gap Report, 2023). In 2018, the US healthcare system was responsible for 8.5 % of US carbon emissions, which had increased from 6 % in 2010 (Dzau et al., 2021; Eckelman et al., 2020). This includes both direct emissions, those due to facilities or vehicles owned by healthcare organizations, and indirect emissions, those due to activities of a healthcare organization such as purchased electricity or supplies manufacturing (Eckelman et al., 2020). The role that healthcare plays in worsening climate change is not lost on most physicians. Amongst obstetrician-gynecologists, 95 % supported reducing waste and 66 % favored reusable surgical tools (Thiel et al., 2017). However, when asked about preferences regarding equipment actually available at their hospital, only 20 % preferred the reusable items (Thiel et al., 2017). A majority were not sure if reprocessed single-use devices were safe or approved by the US Food and Drug

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Administration (FDA), despite reports in the literature indicating no increased risk of infection with their use (Thiel et al., 2017; United States Government Accountability Office [Internet]. [cited, 2024). Thus, a lack of knowledge about the environmental impact of healthcare can hamper sustainability efforts.

The actions of healthcare providers have an environmental impact that ultimately affects the health and well-being of patients. Physicians can play a role in altering the velocity and effects of climate change on patients and the planet. While reviews discussing sustainability in general surgery and general obstetrics and gynecology have recently been published, little has been written about the environmental impact of gynecologic oncology, especially given gynecologic oncology's wide breadth of practice (Wright et al., 2023; Melnyk et al., 2023; Yates et al., 2021). This article offers a review of the ways care of gynecologic oncology patients impacts the environment, from the operating room and radiology to chemotherapy and radiation oncology and proposes ways to mitigate those impacts.

## 2. Energy use in the operating room

The operating room (OR) is estimated to use three to six times more energy than the clinical wards, making it a major contributor to the healthcare carbon footprint (Yates et al., 2021). Examining overhead energy utilization within operating rooms unveils a complex interplay between multiple major consumers of energy, including temperature control and ventilation systems and medical equipment.

### 2.1. Role of heating and cooling systems

The overall energy intensity in the average US hospital stands at 734.5 kW/m$^2$/year, which is three times higher than the typical office building (Bawaneh et al., 2019). Heating, ventilation and air-conditioning (HVAC) systems are estimated to account for 50–75 % of this energy consumption within the OR, playing a crucial role in maintaining air quality and preventing contamination in surgical areas (Čongradac et al., 2012; Teke and Timur, 2014). An estimated 80 % of an operating room's thermal energy demands occur during periods of inactivity (González-Gil et al., 2018).

### 2.2. Surgical equipment energy use

Another significant source of energy expenditure in the operating room is medical equipment. Within the realm of gynecologic oncology, the da Vinci robot (Intuitive Surgical, Sunnyvale, CA, United States of America) is the mainstay tool for managing endometrial cancer. Robotic-assisted and traditional laparoscopy provide several advantages to laparotomy, including lower blood loss, fewer post-op complications, and shorter hospital stay and post-op recovery, with a possibly positive impact on overall survival for endometrial cancer (Fu et al., 2023). Woods et al. conducted a study quantifying the energy consumption during endometrial staging procedures across three surgical modalities: robotic, laparoscopic, and laparotomy. Robotic procedures exhibited the highest electric energy expenditure at 49.6 kWh, surpassing laparoscopic (33.95 kWh) and laparotomy (27.41 kWh). Specifically, the da Vinci robotic system accounted for 20.30 kWh alone (Woods et al., 2015).

### 2.3. Mitigation strategies

There are various strategies physicians and health systems can use to achieve energy savings without compromising patient and staff safety (Table 1). One promising approach involves leveraging off-periods, such as changing HVAC temperature and humidity targets when operating suites are not in use. Cacabelos-Reyes et al. developed a calibrated model demonstrating that adjusting temperature and humidity within recommended international standards during inactive periods could reduce actual energy demands in operating suites by up to 50 % (Cacabelos-Reyes et al., 2020). One study from the University of Minnesota comparing operating rooms at three quaternary-care hospitals showed the site with an HVAC system that prioritized occupancy-based ventilation had a 25–42 % improvement in energy efficiency compared to the other sites with less efficient systems and building infrastructure (MacNeill et al., 2017). As electricity accounts for upwards of 85 % of total inpatient energy expenditures and 3 % of overall operating budget, energy efficiency in HVAC systems can also yield significant financial savings (Bawaneh et al., 2019). There are various subsidies and tax incentives available on the local, state and federal level to encourage healthcare organization investment in energy efficiency (Initiative, 2024). Utilizing down periods and investing in efficient HVAC systems can yield significant energy and financial savings for healthcare systems.

**Table 1**
**Recommendations for Physicians and Healthcare Systems.** A summary of recommendations for improving environmental sustainability in gynecologic oncology, with mitigation opportunities for major contributors highlighted for both physicians and healthcare systems/governments.

| Level of Impact | Topic Area | Key Recommendations |
|---|---|---|
| **Physician Level** | Surgery/ Anesthesia | Practice red bag stewardship |
| | | Limit excess single-use supplies |
| | | Procedure trays > Peel packs |
| | | Shut down robot console when not in use |
| | | Limit use of desflurane, sevoflurane, and nitrous oxide |
| | Radiology | Limit use of CT and MRI |
| | | Power down machines, workstations when idle |
| | Chemotherapy/ Radiation | Support clinical trials for alternative dosing schedules and hypofractionation |
| | Infrastructure | Use telemedicine when able |
| **Hospital & Government Level** | Surgery/ Anesthesia | HVAC efficiency/Idle time shut off |
| | | Encourage industry extended use programs, limited packaging, and recycling |
| | | Purchase reprocessed devices |
| | | Convert to reusable textiles and materials when able |
| | | Invest in gas capture technology research and utilization |
| | Radiology | Use abbreviated protocols and efficient scheduling |
| | | Invest in GABA contrast recycling research |
| | Chemotherapy/ Radiation | Support clinical trials for alternative dosing schedules and hypofractionation |
| | | Invest in chemotherapy pollution research and recycling technology |
| | Infrastructure | Purchase renewable energy sources |
| | | Invest in widespread solar and wind infrastructure |
| | | Electrical grid investment |
| | | Sign on to HHS Climate Pledge |

With regards to energy efficiency of surgical equipment, working with manufacturers to continue to improve energy efficiency of equipment is an important step both physicians and healthcare organizations can take. Data are not readily available about downtime console and patient side cart energy use for the da Vinci system, but when robotic systems are not in use an effort should be made to disconnect from energy sources whenever possible.

When discussing energy use, the source of electricity is perhaps the most important aspect of this conversation. Burning of fossil fuels, such as coal, natural gas, and oil, is a leading source of energy-related carbon emissions (United States Electricity Profile [Internet]. U.S. Energy Information Administration;, 2023). The US Department of Health and Human Services Health Sector Climate Pledge started in 2022 to encourage health organizations to lower greenhouse gas emissions by 50 % by 2030 and achieve net zero emissions by 2050 (Health (ASH) AS for. Health Sector Commitments to Emissions Reduction and Resilience [Internet]., 2022). One scope of this effort is to reduce emissions from purchased steam and electricity by using renewable energy sources, such as solar and wind. Multiple healthcare systems utilize solar energy panels, often located on parking structures, to help offset energy expenditure, including Kaiser Permanente in California, Advent Health in Florida, and North Shore LIJ in New York (Incorporate Solar, 2024; MedCity, 2024). Advocating for more renewable energy, on the organizational, state and national level is a key step in achieving net-zero carbon emissions from health care.

## 3. Environmental impact of OR instruments and supplies

Materials, surgical draping, and single-use instruments also play a significant role in OR carbon emissions, and focusing on decreasing waste and increasing use of reusable materials and equipment can help lower the surgical carbon footprint. To estimate environmental impact of products, many studies use life cycle assessments (LCA) that consider production, use, and end-of-life disposal-related emissions. Carbon dioxide equivalent ($CO_2e$) is a measure that sums up production of $CO_2$ emission and other greenhouse gases by expressing them as equivalent amount of $CO_2$ with the same global warming potential.

### 3.1. *Excess waste and improper disposal*

It has been estimated that at least 20 % of all non-reusable OR waste during hysterectomies is due just to the paper, plastic and glass that package surgical supplies (Thiel et al., 2015). In 2023, Ramani et. al compared the amount of $CO_2$ emissions produced from non-reusable waste between different hysterectomy modalities (Ramani et al., 2023). Robotic hysterectomies used more trash bags and a significantly higher number of surgical gowns compared to laparoscopic, abdominal and vaginal hysterectomies. The total average waste generated by robotic surgery was 26.6 lbs., estimated to be equivalent to 12.01 kg $CO_2e$, significantly more than other modalities (laparoscopic 10.7 kg $CO_2e$, abdominal 7.08 kg $CO_2e$, vaginal 4.5 kg $CO_2e$, $p < 0.001$) (Ramani et al., 2023). In a life cycle assessment of hysterectomies, Thiel et al. had similar findings that robotic procedures produced 30 % more waste than the average alternative approaches at 13.7 kg (30.2 lbs.) of municipal solid waste per case, largely due to the combination of necessary gowns, blue wrap, drapes, gloves, and packaging used per case (Thiel et al., 2015). The former three items are made of polypropylene fabric, also known as spunbond-meltblown-spunbond (SMS PP). SMS PP is used for sterilization wrapping of reusable instruments, and it makes up 22 % of municipal solid waste by weight for robotic hysterectomies and 35 % for laparoscopies (Thiel et al., 2015).

In addition to producing large amounts of non-reusable waste, this waste is often disposed inappropriately. As most are familiar, there are two types of disposal bags to separate waste: red for infectious and pathological waste and clear for noninfectious waste. Misconceptions regarding red bag criteria tend to occur at an individual level. Up to 90 % of red bag contents are inappropriate items, such as paper towels, suction tubes, IV bags, foleys, gowns, drapes and linens that are not saturated in bodily fluids (Kwakye et al., 2011). This oversight can lead to a significantly increased carbon footprint, as 90 % of red bag waste is typically incinerated and only 10 % disposed in landfills (United States Environmental Protection Agency [Internet]., 2016). Incorrect disposal methods are directly associated with environmental and public health concerns (Vinti et al., 2021).

### 3.2. *Reuse and reprocessing*

Equipment reuse and repurposing is an additional avenue to decrease waste and carbon emissions in healthcare. In 2020, Donahue evaluated the carbon footprint of reusable vaginal specula and found that the reusable metal specula had a better $CO_2$ emissions profile than its single-use acrylic counterpart (Donahue et al., 2020). Reprocessing of single-use devices is an additional option to reduce the carbon footprint. More than 60 % of medical devices on the FDA's list of single-use devices are eligible for reprocessing (Register, 2005). One hospital reported saving 2,150 tons of medical waste by diverting it from landfills to reprocessing centers (Kwakye et al., 2010 Mar). Despite the misconception that single-use objects are safer than reusable or reprocessed equipment and that repurposed instruments may be associated with increased surgical site infections, overall there is no benefit with regards to patient safety, surgical outcomes or infection in single use over reusable materials (Smith et al., 2023). Current FDA guidelines do not recommend one choice versus the other (United States Government Accountability Office [Internet]. [cited, 2024).

Robotic surgery instruments are another opportunity for re-use and re-purposing. Each da Vinci Robotic System instrument is limited to a certain number of uses. For example, the monopolar scissors are appropriate for 10 uses, bipolar forceps for 14 uses, needle driver for 15 uses, and Prograsp forceps for 18 uses (Intuitive Inc.;, 2023). Manufacturer initiatives that are helpful in reducing environmental impact include the research into ways to extended number of allowed uses per instrument, programs that recycle outdated or returned equipment, and efforts to reduce packaging.

It is important to recognize that reusable materials still come at an environmental cost from production and sterilization in autoclaves, microwave sterilization systems and chemical disinfection (Thiel et al., 2015; Drew et al., 2021). One study estimated the carbon footprint of a washer/disinfector machine at 3.74 kg $CO_2$ per cycle, while a traditional steam sterilizer emitted 12.13 kg $CO_2$ per cycle (Rizan et al., 2022). When examining impact per instrument, more $CO_2$ emissions were created for instruments that were individually wrapped (145 g $CO_2e$ per cycle) than for items in a set (52.4 g $CO_2e$ per cycle). Surgical sets with more instruments had lower carbon emissions, and those sets utilizing single-use tray wrap (often SMS PP) had the lowest carbon footprint per instrument (13 g $CO_2e$ per use) compared to reusable steel containers (25 g $CO_2e$ per use) and plastic peel pouches (44 g $CO_2e$ per use). The higher emissions for reusable steel containers stemmed from need for additional decontamination. In addition, when examining emissions from sterilization, source of electricity matters, with renewable based sources being an improvement over coal-based (Drew et al., 2021).

### 3.3. *Mitigation strategies*

Decreasing material waste in the operating room will lower overall emissions, from decreasing impacts of the supply chain to disposal (Table 1). When disposables must be used, ensuring they are disposed of in the correct way to reduce improper medical waste incineration is key. Changing from disposable gowns to reusable gowns is one way to reduce OR waste, lower carbon emissions, and not impact infectious risk (McQuerry et al., 2021). If unable to limit use, SMS PP can be recycled and used to make other instruments in both the operating room and hospital at large (van Straten et al., 2021). In addition to reusable textiles, working with industry to improve extended-use programs, less packaging waste, and lower supply chain emissions of robotic and laparoscopic instruments can further lower the carbon footprint of the OR. Swapping out single use materials for reusable or repurposed options generally improves carbon emissions, though source of energy for sterilization methods often is the deciding factor (Rizan et al., 2022). While many hospitals have looked to downsize surgical instrument trays and turn towards single packaged instruments to decrease cost and time, the environmental impact of sterilizing single peel pack instruments should be considered (Rizan et al., 2022). Physicians and the healthcare system as consumers have the responsibility to shape industry behavior by communicating that these sustainable practices are important in purchasing and practice decisions.

## 4. Anesthesia impacts

In addition to the impacts of energy use and material waste, anesthesia practices substantially contribute to the environmental footprint of the operating room. Certain inhaled anesthetics are greenhouse gases, making it crucial to collaborate with anesthesia colleagues to adopt methods with lower greenhouse gas emissions and implement systems to mitigate these impacts. These efforts are essential for reducing healthcare's contribution to climate change.

### *4.1. Greenhouse gas emissions and ozone layer impacts*

Anesthesia practices, particularly the use of volatile anesthetics like desflurane, sevoflurane, and nitrous oxide, contribute to greenhouse gas emissions. The global warming potential of inhaled anesthetics is hundreds of times greater than an equivalent mass of carbon dioxide (American Society of Anesthesiologists Committee on Environmental health. The Environmental Impact of Inhaled Anesthetics [Internet]., 2024). Volatile anesthetics and nitrous oxide ($N_2O$) are potent greenhouse gases, and $N_2O$ also contributes to depletion of the ozone layer (American Society of Anesthesiologists Committee on Environmental health. The Environmental Impact of Inhaled Anesthetics [Internet]., 2024). These gases, while constituting a small fraction (0.01–0.1 %) of total emissions, have a disproportionately high impact due to their potency as greenhouse gases. With desflurane and nitrous oxide, equivalent carbon dioxide emissions are approximately 40 times greater than those related to sevoflurane at similar gas flow rates (McGain et al., 2020). Anesthetic gases, particularly desflurane, sevoflurane, and nitrous oxide, contribute to global warming and can impact the ozone layer, exacerbating environmental concerns. These volatile anesthetics undergo minimal in vivo metabolism and are released into the troposphere with minimal changes, accounting for over 95 % of their emissions (Sherman et al., 2012). Sevoflurane and desflurane persist in the troposphere for approximately 1.1 and 14 years, respectively (Sulbaek Andersen et al., 2010).

### *4.2. Anesthesia emissions in gynecologic surgery*

A life cycle assessment for hysterectomies in the United States reveals that anesthesia administration accounts for a significant portion of greenhouse gas emissions associated with different types of hysterectomy procedures (Thiel et al., 2015). On average, anesthetic gases contributed to a third of the greenhouse gas emissions of robotic and laparoscopic hysterectomies and two-thirds of abdominal and vaginal hysterectomies. For abdominal and vaginal hysterectomy, anesthetic use contributed to 98 % of the ozone depletion potential (Thiel et al., 2015). This emphasizes the need to consider anesthesia practices when assessing the environmental footprint of surgical procedures.

### *4.3. Mitigation strategies*

Mitigation approaches include minimizing the use of high-impact anesthetics like desflurane, sevoflurane, and nitrous oxide, and promoting the use of regional anesthesia and propofol when feasible (Table 1). Inhaled anesthetics have a higher life-cycle emissions compared to propofol, a commonly used intravenous anesthetic, when considering factors such as manufacturing, equipment, administration, and disposal (Sherman et al., 2012). This suggests that transitioning to alternative anesthesia methods like propofol can help reduce environmental impact from a carbon emissions standpoint. However, it should be noted that propofol accounted for 45 % of total operating room drug waste and an estimated 50 % of propofol prepared for each surgery was wasted. While propofol that is injected is extensively metabolized with little unmetabolized drug that is excreted, wasted propofol that is may end up in in the environment where its impacts on water quality and wildlife are unknown (Sherman et al., 2012).

Additionally, gas capture and recycling technologies, although not widely used in the United States, have been implemented in other regions like Canada and Europe, indicating potential for broader adoption (Ahn et al., 2023). Although interest in environmental sustainability in anesthesia practice is growing, implementing sustainable practices still needs to overcome many barriers. Several studies have shown that only about a third of anesthesiologists incorporate environmentally-conscious practices into their daily work (Ard et al., 2016).

Collaboration between surgical and anesthesia teams is essential for implementing strategies to reduce environmental impact. Fostering collaboration between gynecologic oncology and anesthesia teams will make it possible to optimize anesthesia practices and advocate for more sustainable approaches in the operating room. Patient safety should not be affected by the implementation of sustainable anesthesia practices. Lower carbon emitting medicines, equipment and techniques should only be used when clinically safe to do so (White et al., 2022).

Advocating for the adoption of more efficient systems and technologies in the future is crucial for lowering the environmental impact of operating rooms. The World Federation of Societies of Anesthesiologists, in a global consensus statement, advises incorporating environmental sustainability principles within formal anesthesia education (White et al., 2022). In the United Kingdom, for instance, the postgraduate curriculum for anesthetic training involves the principles of sustainable healthcare (College, 2021).

The significant environmental impacts of anesthesia practices highlight the importance of incorporating these considerations into the broader context of environmental sustainability in healthcare settings. This underscores the need for collaborative efforts to mitigate their impact.

## 5. Radiology impact

While most of the carbon footprint from gynecologic oncology is attributed to operating room procedures, there is also an impact from radiologic imaging and associated contrast materials.

### *5.1. Impacts of imaging modalities*

Medical imaging is a significant contributor to healthcare's greenhouse gas emissions. A life-cycle assessment of radiologic modalities concluded that the smallest $CO_2e$ was seen with ultrasound (1.2 kg $CO_2e$ per examination), with computed tomography (CT) and magnetic resonance imaging (MRI) producing five and 20 times as much $CO_2e$ per examination (6.6 kg and 19.7 kg $CO_2e$ per examination, respectively) (Martin et al., 2018). These differences are especially relevant to gynecologic oncology given the rise in the incidence of endometrial cancer and the resultant increase in demand for diagnostic imaging and radiotherapy (Somasegar et al., 2023).

### *5.2. Operational energy use*

The increasing demand for diagnostics is expected to result in a 30 % increase in $CO_2e$ from CT and MRI by 2030 (Kouropoulos and Pessoa, 2018). Increasing demand that drives new infrastructure development is problematic, even when scanners are not actively used, since energy consumption and $CO_2e$ occur during idle states as well. One study found that two-thirds of yearly energy consumption for CT scanners and one-third of yearly consumption for MRIs occurred during idle states (Heye et al., 2020).

### *5.3. Interventional radiology and contrast waste*

Approximately 10 % of total healthcare carbon footprint is due to clinical radiology and radiotherapy waste, mainly from interventional procedures (Brown and Forster, 2022). Interventional radiology (IR) procedures are often used by gynecologic oncology to aid in diagnosis, provide central vascular access, and treat complications that arise. Much of the carbon footprint from interventional radiology can be traced to a high volume of single use products, such as coils, syringes, wires, and catheters (Brown and Forster, 2022).

Contrast agents such as iodinated media and gadolinium-based contrast agents (GBCA) have been detected in drinking water (Dekker et al., 2022; Brünjes and Hofmann, 2020). GBCAs in their clinically used form are non-toxic due to the use of chelates that are specifically designed for high stability (Caravan et al., 1999). The current wastewater treatment processes do not entirely degrade the most stable GBCAs. However, given enough time, all the GBCAs released into wastewater will eventually be degraded to free gadolinium, which is a known environmental toxin (Brünjes and Hofmann, 2020). The indiscriminate disposal of GBCAs into wastewater is also unsustainable based on the availability and cost of inorganic gadolinium reagents obtained directly from mineral sources and the energy consumed to synthesize the gadolinium reagent (Chawla et al., 2017).

### 5.4. Mitigation techniques

Carbon emissions from radiologic procedures for gynecologic cancer can be mitigated in a number of ways (Table 1). Choosing the right imaging modality for the initial diagnosis and surveillance for gynecologic cancers can significantly lower carbon emissions. Decisions about imaging balance potential information gained in a specific clinical situation, the risk of radiation, the economic cost, and the environmental cost. While ultrasound is a useful tool for the initial workup of abnormal uterine bleeding or postmenopausal bleeding and yields the lowest carbon emissions, it is not as useful for the detection of metastatic disease (Expert Panel on GYN and OB Imaging et al., 2020). Contrast enhanced MRI can be used for initial staging and treatment planning in endometrial cancer given its ability to assess the presence and extent of myometrial invasion and local tumor extent, especially when fertility sparing surgery is being considered (Expert Panel on GYN and OB Imaging et al., 2020). CT scans are useful in the context of assessing the presence and response to treatment of metastatic disease. Limiting utilization of higher $CO_2$ emitting modalities such as CT and MRI to truly necessary clinical situations can decrease radiologic carbon emissions.

While judicious use of higher carbon emitting radiology modalities is important, so is optimizing scanner use and efficiency to decrease environmental impacts. Turning off CT scanners and some components of the MR scanner when not in use are measures that can be implemented today in most centers. At the University of Kentucky, the Department of Radiology has implemented measures to shut down components of the MRI scanner during periods of inactivity. A sensitivity analysis that used fixed lifetimes for each machine found a decreased $CO_2$e per examination when the machines were operated 24 h a day, seven days a week vs. nine hours a day since the production phase $CO_2$e was apportioned among a larger number of examinations (Martin et al., 2018). Common-sense initiatives such as workstation auto-shutdown and motion-sensing light-emitting diodes (LED) lights in radiology departments can further lower the environmental impact and are tactics that can be applied to healthcare spaces in general (Platzek et al., 1997). Thus, optimal use of existing scanners by improving scheduling, using abbreviated protocols so that requisite information is obtained with less total energy usage per examination, and judicious use of imaging are all strategies to reduce the impact of imaging.

Finally, given the potential ecological and carbon emission impacts of gadolinium contrast, developing new approaches to prevent pollution with such agents is critical to mitigating their environmental impact. For example, the University of Kentucky is developing new technologies to recycle GBCAs and extract the element from aqueous sources.

Awareness of the environmental impact of radiographic studies and materials allows us to make informed decisions that balance patient care with environmental sustainability.

## 6. Chemotherapy and radiation oncology impact

### 6.1. Chemotherapy

Carbon emissions from use of energy and materials is not the only sustainability concern within gynecologic oncology, as chemical pollution is also a threat to the environment (Laurent et al., 2012). The disposal of chemotherapy agents contributes to pollution and ecological harm. Typically, these medications are collected and filtered in a wastewater treatment plant. Most anticancer drugs are broken down through water treatment; however, studies have found persistent levels of some anticancer medications in river water (Ferrando-Climent et al., 2014). Parent drugs and metabolites can have cytotoxic and genotoxic effects on animals and plants that they interact with, such as changes in expression of genes involved in DNA damage, apoptosis and oncogenesis (Gajski et al., 2016). Platinum containing chemotherapies such as carboplatin and cisplatin have been found in hospital wastewater at concentrations of more than 760 ng per liter, and exposure to 14 ng/liter has been shown to impact reproduction in crustaceans (Folens et al., 2024). Antineoplastic drugs such as ifosfamide, methotrexate, tamoxifen and cyclophosphamide have all been shown to disrupt the organisms exposed to these agents causing far-reaching ecological consequences (Yin et al., 2010). In addition to environmental pollution from wastewater, paclitaxel is derived from the Yew tree, and while many efforts have been made to develop a cheaper and more environmentally sustainable form of the drug synthetically, paclitaxel extraction from Yew trees is still the most frequent form of production (Gallego-Jara et al., 2020). It is estimated that four Yew trees are needed to produce two grams of paclitaxel (Gallego-Jara et al., 2020).

### 6.2. Radiation oncology

The environmental impact of radiation oncology is also an important aspect of the discussion of sustainability in gynecologic oncology as it is the main treatment modality of cervical cancer and a frequently used treatment in adjuvant endometrial and recurrent vulvar cancer. One recent life cycle assessment performed across multiple institutions in the US estimated the mean greenhouse gas emissions for a standard 25-fraction external beam radiation therapy course for gynecologic cancers at 4,120 kg $CO_2$e, with building energy use making up 77 % and patient and staff transit 22 % (Lichter et al., 2024). Across all cancer types, building energy use was the highest contributor to $CO_2$ emissions, with HVAC systems leading those emissions and equipment for radiation therapy (computers, CT scanners, electrometer, linear accelerator) making up approximately 3 % of overall emissions (Lichter et al., 2024).

### 6.3. Mitigation techniques

Given their widespread clinical use, advocating for research on the environmental impact of chemotherapy in wastewater is crucial for the understanding of sustainable practices within the field. Additionally, recycling of chemotherapy components from wastewater may be possible. For example, carboplatin is especially stable in wastewater, and recycling of platinum compounds to decrease environmental impacts has been proposed (Folens et al., 2024).

Alternative doses of chemotherapy and infusion immunotherapy to decrease the number of visits required may also improve environmental impact of these medications through reducing patient travel, material waste, and overall production emissions for both infusions and any pretreatment medications. One recent study modeled alternative pembrolizumab dosing using retrospective data from Veterans Health Administration from 2020 to 2022 (Bryant et al., 2024). After extracting dosing information from over 7000 veterans with a variety of malignancies who received pembrolizumab, three dosing protocols using either 4 mg/kg every six weeks or 400 mg every six weeks was used to model expected reduction in travel, medical waste and drug manufacture-associated greenhouse gas emissions. The 400 mg every six week protocol was associated with a 20 % reduction in metric tons of $CO_2$ emissions due to fewer miles traveled by patients (Bryant et al., 2024). 400 mg every six weeks is already an FDA approved pembrolizumab dose for cervical and endometrial cancer (Pharmaceuticals, 2024). This strategy highlights how dose adjustments can lower carbon emissions through reduction in patient visits, which would also lead to less financial strain on patients and their caretakers.

Reducing frequency and visits required is also a strategy to reduce emissions in radiation oncology. One possibility includes hypofractionation, where the number of fractions is reduced at expense for higher per fraction dose to administer radiation in a shorter treatment plan. Modeled hypofractionation plans in breast and genitourinary cancers showed a 44 % decrease in overall carbon emissions as patients required less treatment sessions and associated travel (Lichter et al., 2024). Another study found hypofractionation in rectal cancer resulted in 80 % reduction in greenhouse gas emissions, with the per patient amount of $CO_2$ emissions equaling those from electricity use in the average American home for 37 days (Frick et al., 2023). While hypofractionation is widely used in breast and prostate cancer, it is not standard in GYN cancers and its comparable efficacy is presently unknown, though it is being actively researched in clinical trials (Amjad et al., 2024).

Additionally, patient travel to appointments and treatments is another source of carbon emissions in the realm of gynecologic oncology care. The COVID-19 pandemic increased the use acceptance of telehealth, which for visits that do not necessitate an exam is an option to not only provide financial and time savings to patients but also decrease $CO_2$ emissions (Jiang et al., 2021). One study focused on gynecologic oncology visits from the University of Wisconsin estimated that utilizing telemedicine for 50 % of encounters during the COVID-19 pandemic prevented 6.25 metric tons of $CO_2$ emissions from patient travel with high levels of patient satisfaction (Mojdehbakhsh et al., 2021). Given that upwards of 90 % of US counties lack a gynecologic oncologist and 21 % of adult women in the US live over 50 miles from a gynecologic oncologist, awareness of patient travel and its impact on carbon emissions is important (Desjardins et al., 2023; Ackroyd et al., 2021). Outside of utilizing telemedicine when possible, establishing outreach clinics in communities without a gynecologic oncologist for surgical consultations and chemotherapy is another avenue to reduce carbon emissions with respect to patient travel (Forner et al., 2021).

## 7. Conclusion

There are many opportunities for improved environmental sustainability within gynecologic oncology (Table 1). Reducing idle-time energy use, improving HVAC system efficiency, and practicing material stewardship can lower operating room carbon emissions. Decreasing the use of environmental deleterious inhaled anesthetics and advocating for the implementation of gas recapture technology can help mitigate the effects of anesthesia. In addition, working with radiology colleagues to practice judicious use of imaging and improving imaging efficiency, while also advocating for research into gadolinium recapture from wastewater can further improve the environmental impact of gynecologic oncology. Finally, alternative dosing of chemotherapy and radiation, in addition to telemedicine, can decrease the carbon emissions from patient travel, while also saving patients time and financial resources. While there is no easy answer for minimizing the effects of climate change, as a subspeciality we can recognize our part in minimizing healthcare's impacts on the environment and work with our colleagues in other parts of medicine to address these challenges to protect the health and wellbeing of not only our patients but our larger community.

## CRediT authorship contribution statement

**Allison L. Swiecki-Sikora:** Writing – review & editing, Writing – original draft, Conceptualization. **Mariel V. Becker:** Writing – original draft, Conceptualization. **Laura M. Harbin:** Writing – review & editing. **Elizabeth Knapp:** Writing – review & editing. **Rashmi T. Nair:** Writing – review & editing, Writing – original draft. **Marcelo I. Guzman:** Writing – review & editing, Writing – original draft. **David A. Atwood:** Writing – review & editing, Writing – original draft. **Syed Z. Ali:** Writing – review & editing, Writing – original draft. **Charles S. Dietrich:** Writing – review & editing, Supervision, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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